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WATERSPOUT-TORNADO STRUCTURE AND BEHAVIOR AT NAGS HEAD, N.C., AUGUST 12, 1952

FRANK B. DINWIDDIE¹

Nags Head, N.C.

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ABSTRACT

This note describes (1) a situation leading to the anticipation of waterspout formation, (2) three spouts which subsequently formed, and (3) the passage of the third spout over the observer. An interpretation of the first spout's formation, and of the third spout's lower structure, is proposed.

1. WEATHER CONDITIONS

The formation of tornado-waterspouts was expected at Nags Head, N.C., shortly after 1500 EST, August 12, 1952, when conditions resembling those of July 8, 1942, and June 20, 1945, which then led to waterspout formation [1], were observed. The situation is shown in figure 1b; a warm NE sea breeze at Nags Head, the location of the observer, was opposed by a warm SSW wind, with a solid line of convective clouds between. Figure 1a shows the background events leading to the formation of the cloud line. The clouds moved almost from the WSW with a slow drift toward Nags Head. Above the NE breeze, fractocumulus moved from the SW, and also cumulus from the WSW. Temperature in the NE breeze was 90° F., dewpoint 78° F., and pressure was 30.00 inches and falling. The temperature of the sea surface at shore was 72° F.

2. FORMATION OF VORTICES

Vortex circulation was expected if the NE breeze reached the cloud level (fig. 2b). As rain began falling

from the rear of the cloud line (cross-hatched area in fig. 2a), I took the first 35-mm. color photograph of the tornado sequence. The next 20 minutes were uneventful, until suddenly fractocumulus shreds moving from the NE, as shown in figure 2a, appeared below the nearer edge of the cloud base, opposite the rain. The cool air dome accompanying the rain (fig. 2b) could have been the mechanism which at this point lifted the NE sea breeze into the convective cloud cell where its energy contribution (horizontal momentum favoring the start of cyclonic circulation, as in fig. 2a, and latent heat release favoring vertical exhausting) appeared to trigger the dramatic events that followed.

From here on things happened fast. The shreds grew up into the cloud base, and almost immediately a tornado cyclone was born within the cloud, causing the entire width of the base opposite (that is, north of) the rain to rotate in a circle 2 or 3 miles across, the nearer edge moving from the NE and the whole disturbance accelerating to relatively high speed. The straight edge of the cloud line was quickly bent into a wave, so that the nearer edge retreated toward the SSE (figs. 2a and 3). In a few minutes a new rotation appeared along the back of the

¹Cooperative Weather Observer, U.S. Weather Bureau.

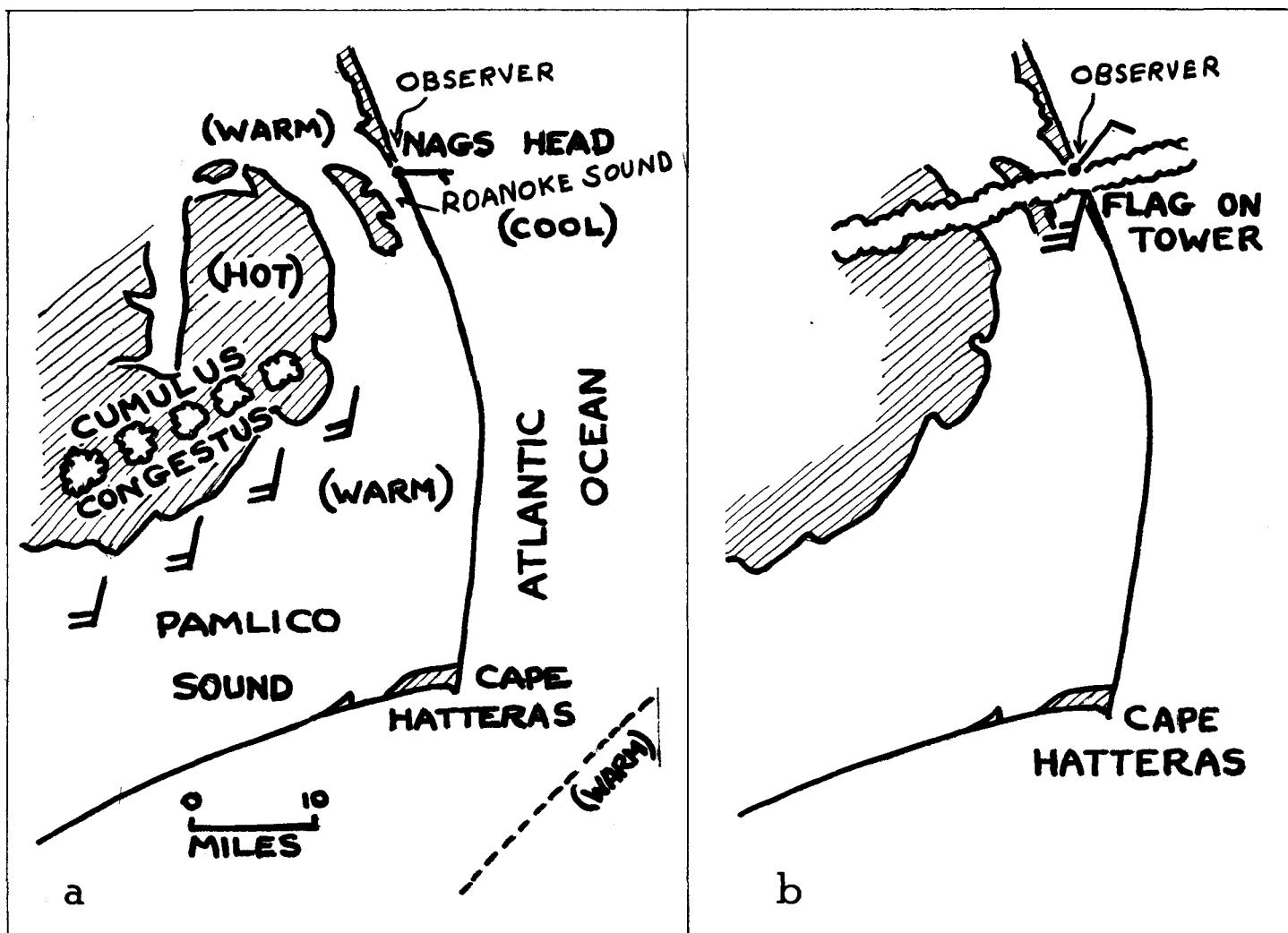


FIGURE 1.—(a) Distribution of surface heat and surface wind, and location of first cumulus congestus, 1230 EST, August 12, 1952. (b) Location of developed cumulus congestus convective line, and adjacent surface wind, 1500 EST, August 12, 1952.

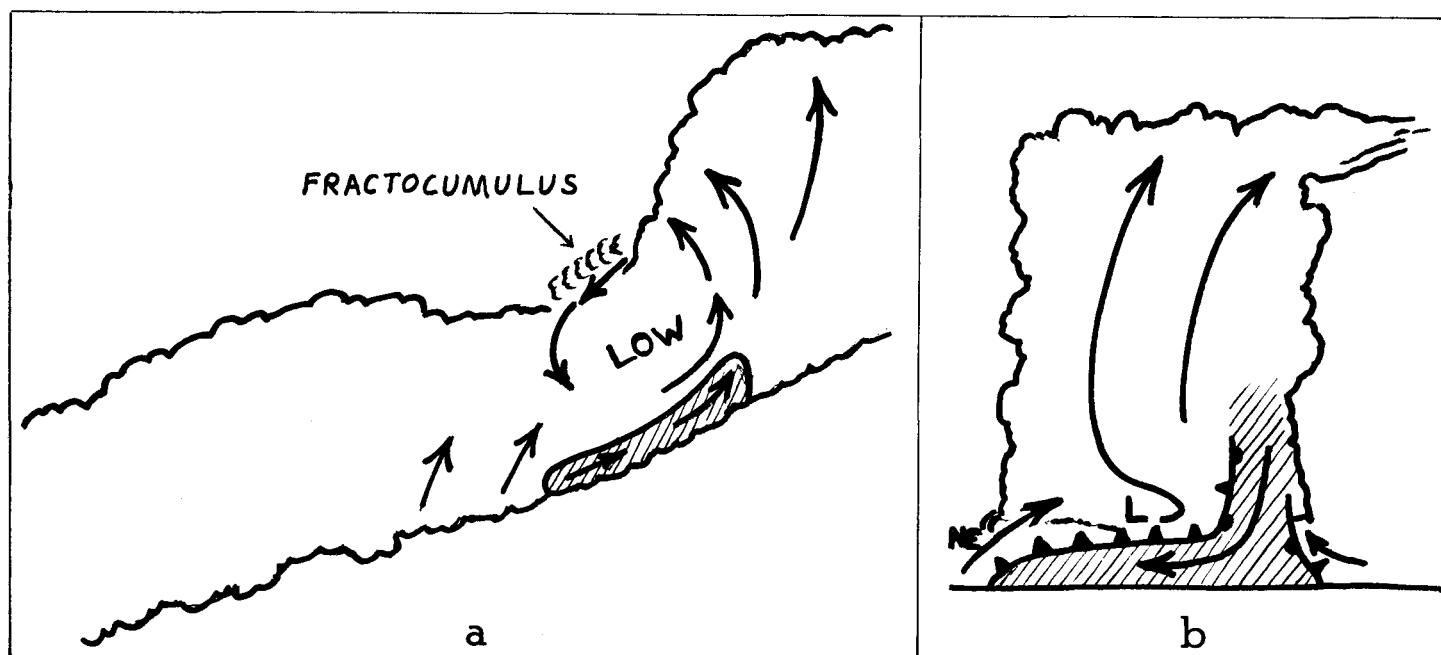


FIGURE 2.—(a) Plan sketch (just above cloud base level) and (b) elevation sketch of storm cloud line as rotary motion began.

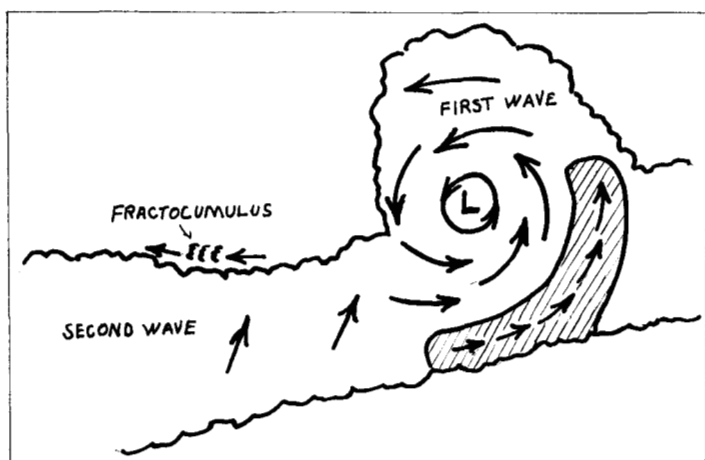


FIGURE 3.—Plan sketch of storm cloud line (just above cloud base level) a short time after figure 2.

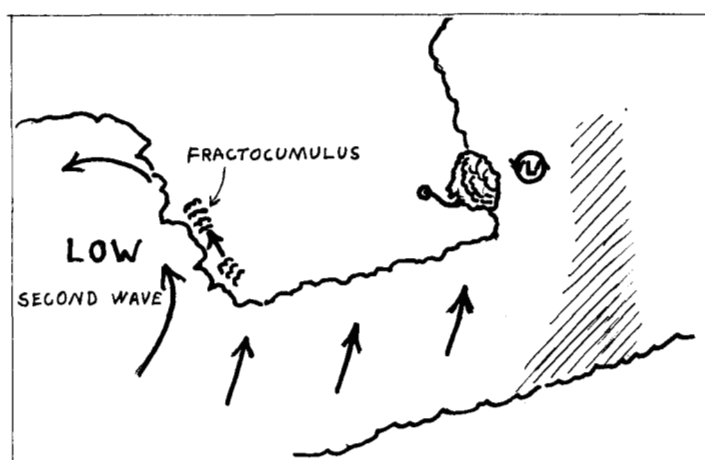


FIGURE 6.—Plan sketch of cloud line (just above cloud base level) following figure 3 and at time when first spout (right center) had formed. Rain distribution shown by cross hatching.

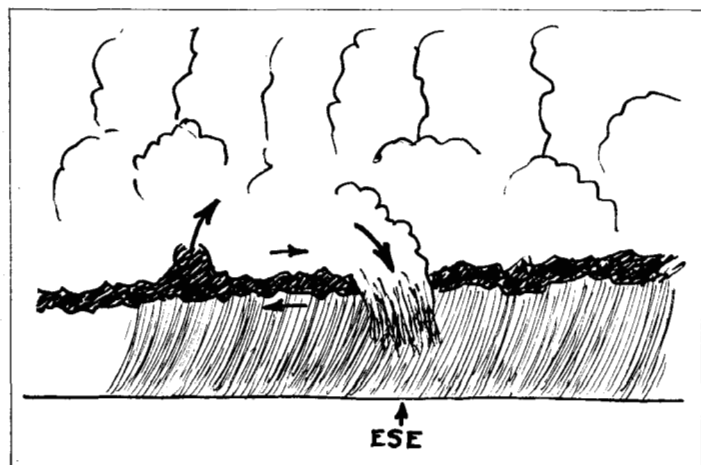


FIGURE 4.—Development of rotary movement with inclined axis in cumulonimbus base. Drawn from memory.

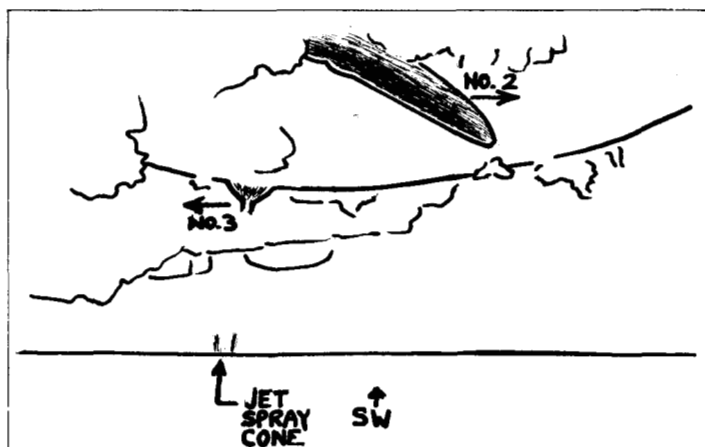


FIGURE 7.—The appearance of the second and third waterspouts depending from rotating, bowl-shaped depression at base of the second wave in cumulonimbus line. Drawn by the author from a color transparency.

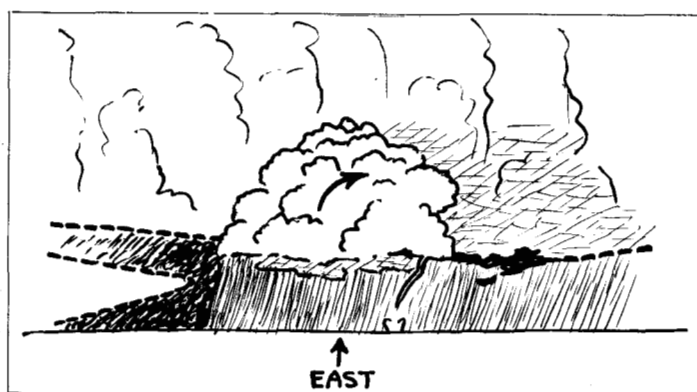


FIGURE 5.—Appearance of first waterspout depending from small rotating cumulus at rear of wave in cumulonimbus line. Drawn by the author from a 35-mm. color transparency.

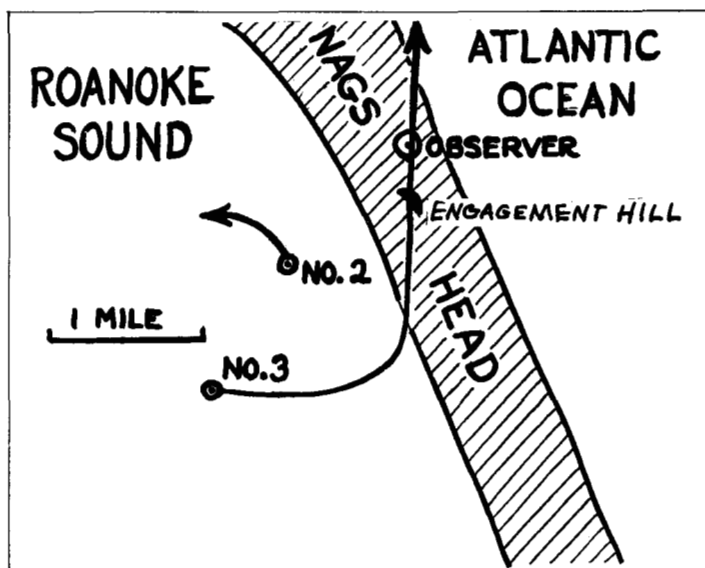


FIGURE 8.—Tracks of waterspouts 2 and 3.

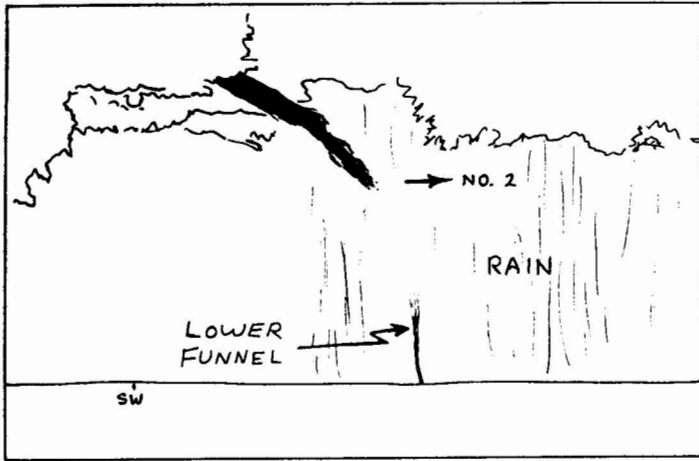


FIGURE 9.—Upper and lower vortex clouds of waterspout no. 2, which merged into a continuous vertical tube as the spout died. Rain is falling from the rear of the second wave. Drawn by the author from a color transparency.

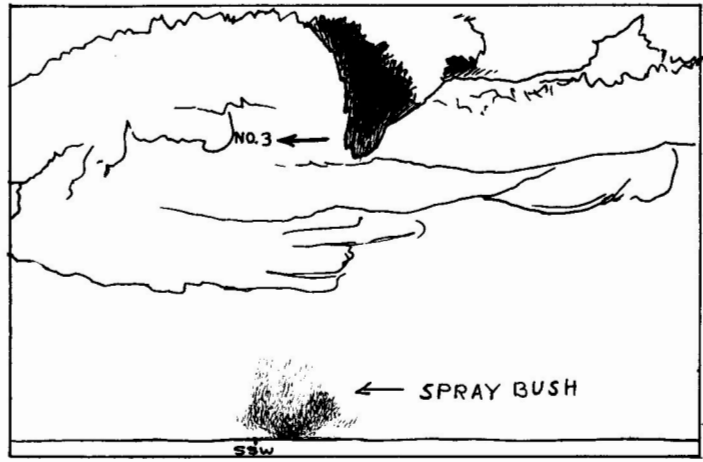


FIGURE 10.—Waterspout no. 3 moving east with thick funnel and well-developed spray bush about 400 ft high. Drawn by the author from a color transparency.

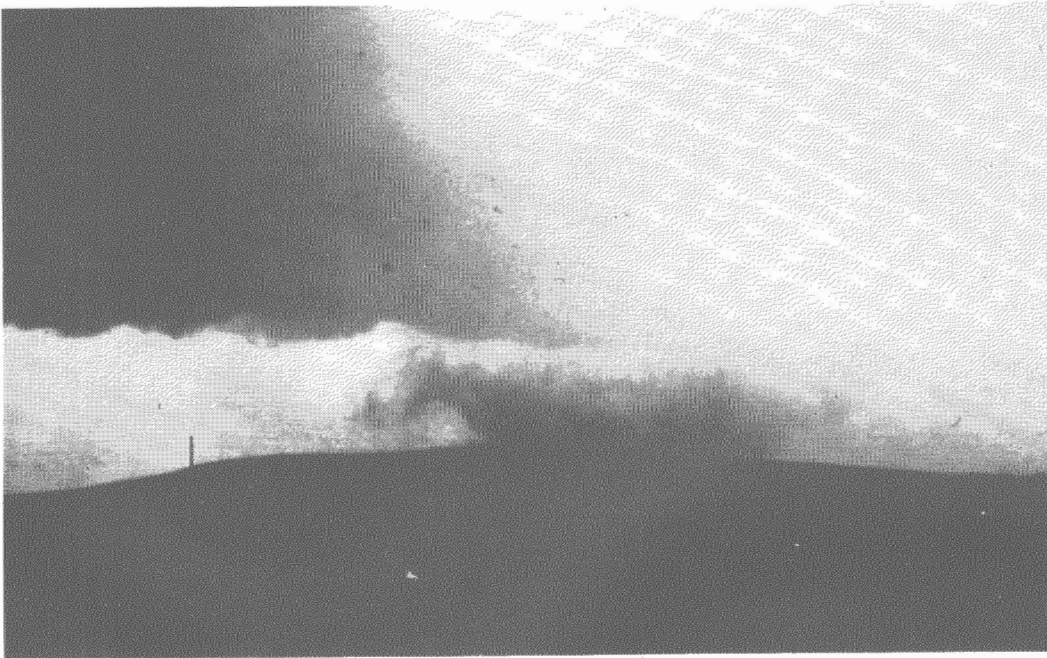


FIGURE 11.—The sand bush of waterspout no. 3 on top of Engagement Hill, 600 yards distant and moving north toward the observer. Reproduced from a color transparency. The lighter part of the sky at the right is a heavy curtain of rain following close behind the spout, and probably illuminated by sunlight reflected from water.

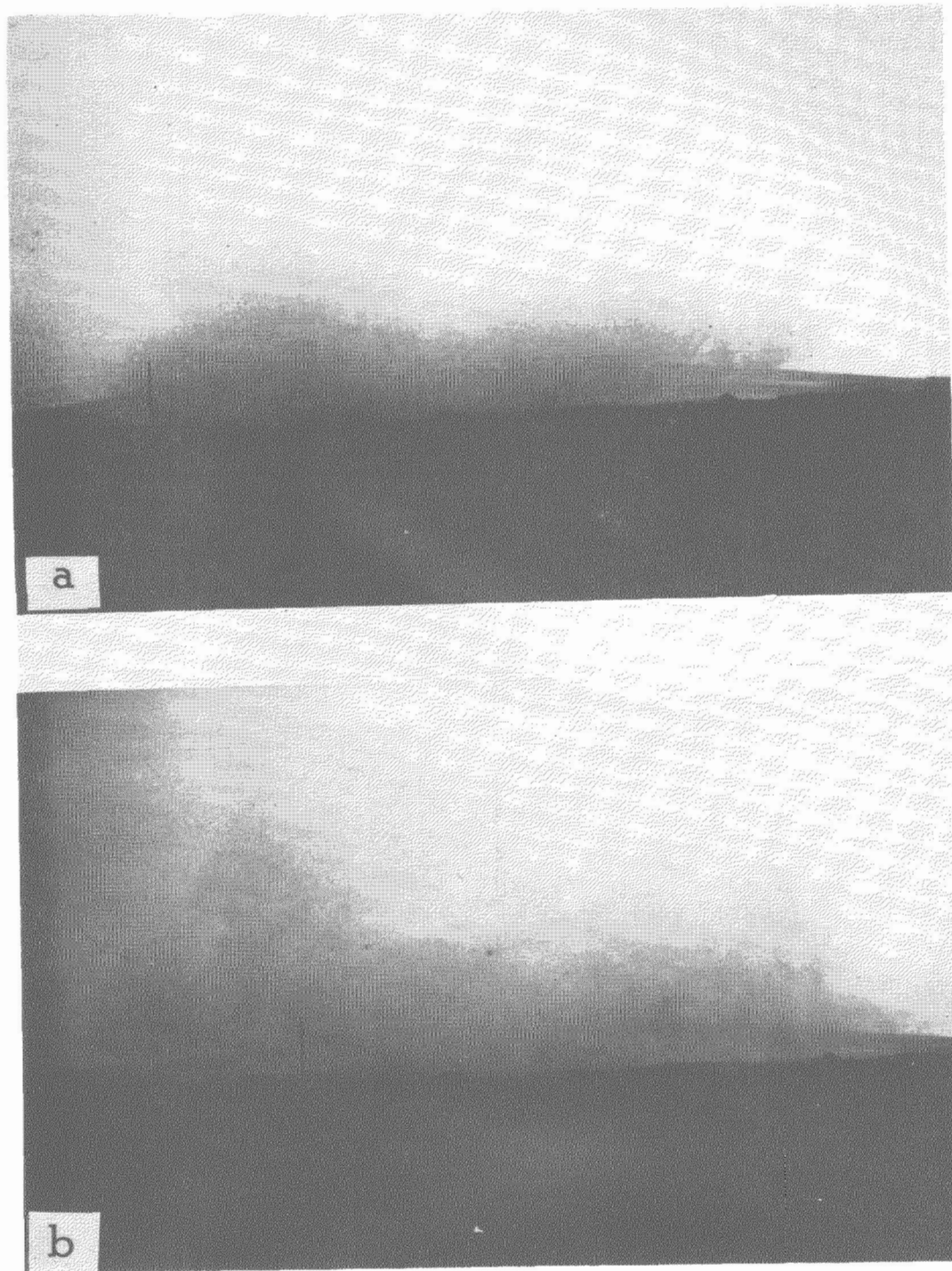


FIGURE 12.—(a) The sand bush of waterspout no. 3 at the base of Engagement Hill, about 400 yards distant. Reproduced from a color transparency. The heavy rain curtain seen in figure 11 has spread rapidly eastward and fills almost the entire sky area in this picture, giving the illusion of a clear sky. (b) This reproduction from the color shot shows the sand bush about 300 yards from the camera. The core wall reached near the top of the picture in two peaks. The outfall ring reaches to the edge at the right and nearly so to the left. The jet core shows dense at the center, between the electric wires and the black foreground. The convergence disk lightens the surface of the hill near its foot under the outfall ring.

wave, within the first whirl, but smaller, and with its axis inclined to the vertical, so that one part of the cumulonimbus edge was lifted, and another part to the right forced to plunge rapidly earthward as in figure 4. As this motion accelerated, the first larger whirl quieted, and presently from the concentrated turmoil the vortex cloud suddenly appeared over its whole length (that is, did not build downward)—thin, crooked, quivering, and silvery white against the dark rain background. Spray leaped up like a white bush at its base. The cloud tube depended from a soft-appearing, slowly turning cumulus which protruded westward and slightly downward from the lower wall of the cumulonimbus in the rear of the wave (figs. 5 and 6). The wave moved ENE and disappeared in rain, while the spout lagged behind and elongated horizontally, and finally disappeared about 10 minutes after its beginning.

Meanwhile a new wave developed to the SW of my location, with fractocumulus skirting its base, moving from the E (fig. 3), then from the SE (fig. 6) as the wave increased its activity. Soon the base of this wave was in rapid rotation, 2 or 3 miles in diameter, which *quieted* when two new tornadoes appeared at about 1630 EST over Roanoke Sound (located in fig. 1a), roughly $\frac{3}{4}$ and 2 miles, respectively, SW of the observer. Their appearance is sketched in figure 7. These followed counterclockwise orbits about each other (fig. 8) for about 10 minutes, the farther spout, no. 3, later passing over the observer. The nearer spout, no. 2, evolved into separate tubes as in figure 9; these tubes merged shortly before the spout dissolved.

In its early moments this spout showed a brief, wave-like down-rush along the upper funnel for two or three seconds, which did not lengthen the upper funnel, and which was not seen to affect the lower funnel. It accelerated from rest, and decelerated back to rest, quickly and smoothly. It was much faster than the normal rotary motion of the funnel; in fact, while it lasted, no rotary component of motion was even discernible—it looked to be entirely longitudinal with the vortex axis. Later, a similar less intense uprush was observed. It looked like an adjustment of internal pressure whose velocity along the funnel varied directly with height above the ground. The maximum velocity, if the cumulonimbus base was 2,000 feet high, was at least 500 m.p.h. With these two exceptions the spout cloud showed no evidence of vertical movement. No spray bush was discernible with this spout.

3. EVOLUTION OF TORNADO

Meanwhile spout no. 3, with a short thick funnel aloft and a spray bush about 400 feet high as in figure 10, moved eastward as shown in figure 8, and disappeared beyond Engagement Hill (located in fig. 8), a 60-foot sand dune 2,000 feet south of the observer. Its dissolution was, mistakenly, assumed. Two minutes later the top of

Engagement Hill suddenly erupted into a whirling yellow monster of flying sand 200 feet high and 600 feet wide. It was bearing down on the observer at about 35 m.p.h. Figure 11 is a photograph of the whirling sand as it came across the top of Engagement Hill. It was about 600 yards distant at the time. Twenty seconds later the faint swishing sound became a heavy roar as the waterspout-turned-tornado advanced across the grassy, bushy field at the base of the hill. It was tossing thick-branched myrtle bushes aloft and reports like gunfire occurred as their roots severed. The appearance of the whirling sand is shown in figure 12a, a photograph made when the base of the tornado was about 400 yards distant. Another photo, figure 12b, shows the whirling sand bush when about 300 yards away. Details of its structure are described with the figure. Another 15 seconds and the observer's house, and probably the observer, began to shake in the wind of the tornado, and as the last photograph was made, when the tornado was only 90 yards distant as in figure 13a, brief refuge was sought indoors. In the dream-like confusion of the next several seconds there was a detached awareness of a great roar, a blur of flying sand, and the house shaking, objects tumbling inside, and a dull thud outside as a door left the house and overturned a refrigerator on the porch in departing. There was also a shower of timbers about the house, ranging in cross section up to 3 x 8 and 2 x 12 inches. Almost all of them were split and broken by the storm, yet they were lowered so gently to the earth that the soft sand around them was undisturbed.

Immediately after the surface manifestation of the tornado had passed, the short, suspended funnel was observed to be still south of the house, about 60° high, but in a few seconds it passed overhead toward the north. The surface whirl, retreating to the north, resembled a flock of circling birds with its temporarily suspended boards, boxes, garbage cans, etc. None of these objects, on falling, was identified over 450 feet from its original position. The twister passed out to sea a half-mile north of the observer, and briefly developed a cloud tube from sea to clouds, 50 to 70 feet in diameter, before disappearing entirely.

During the passage of the tornado in the vicinity of the house a 400-lb. boat, containing 1,000 lb. of rainwater had been tossed into telephone wires, then through a fence, and its parts carried 450 feet. Piles of fish boxes and lumber had been scattered about 400 feet. Eight buildings suffered minor damage. An iron pump in a fenced garden was sheared from its pipe and driven hard into the sand 10 feet away, and the surrounding fences were flattened outward. Details of objects moved and the path of the tornado are shown in figure 14.

Surface winds were light E to SE just before the storm hit at 1640 EST. Five minutes later torrential rain without hail, but with very severe lightning and thunder, was blown by a S wind of force 4, which in another five

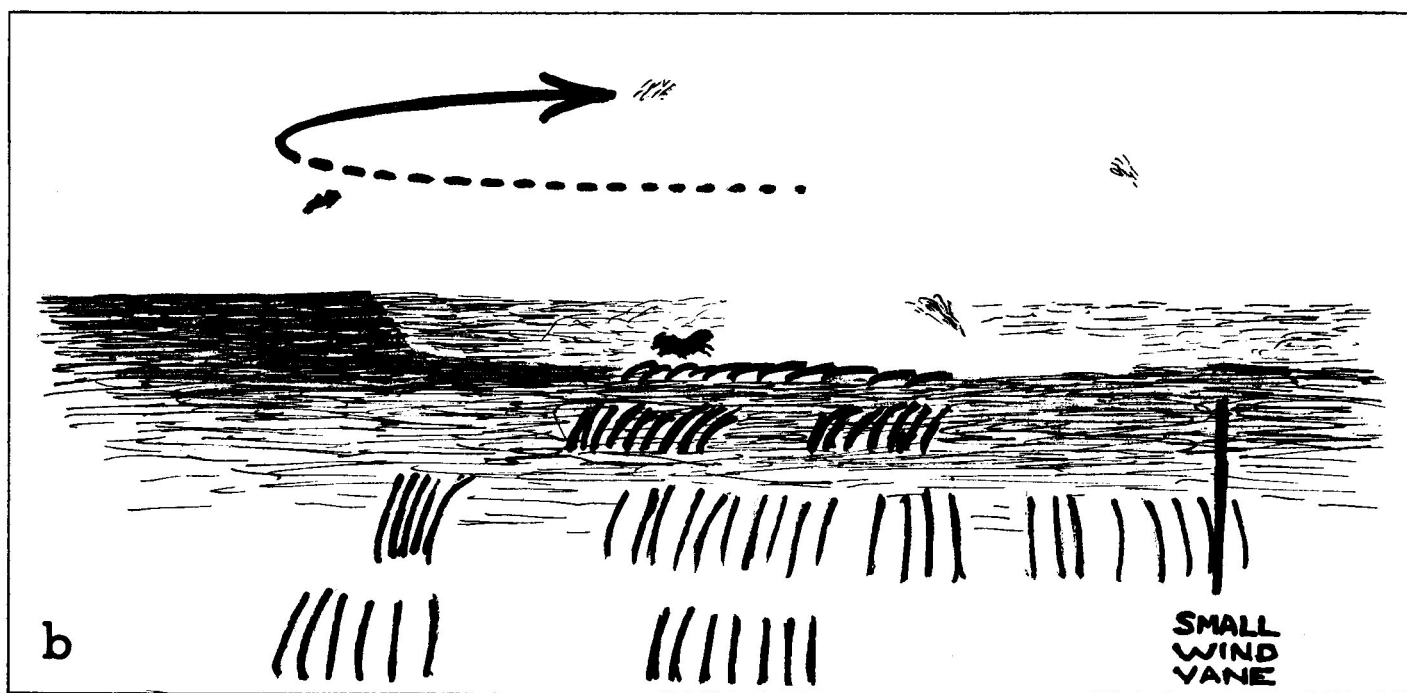


FIGURE 13.—(a) Reproduction from a color transparency showing view of tornado center about 90 yards distant, with observer in area of strong convergence. The tall beach grass, and wind vane turned endwise and therefore invisible, indicate how airflow was toward the center without cyclonic movement in outer part of convergence zone. Center is over shallow ditch located at bottom of figure 14. (b) Simplified sketch drawn from (a) to emphasize representative tufts of bending grass, and the wind vane support at the right.

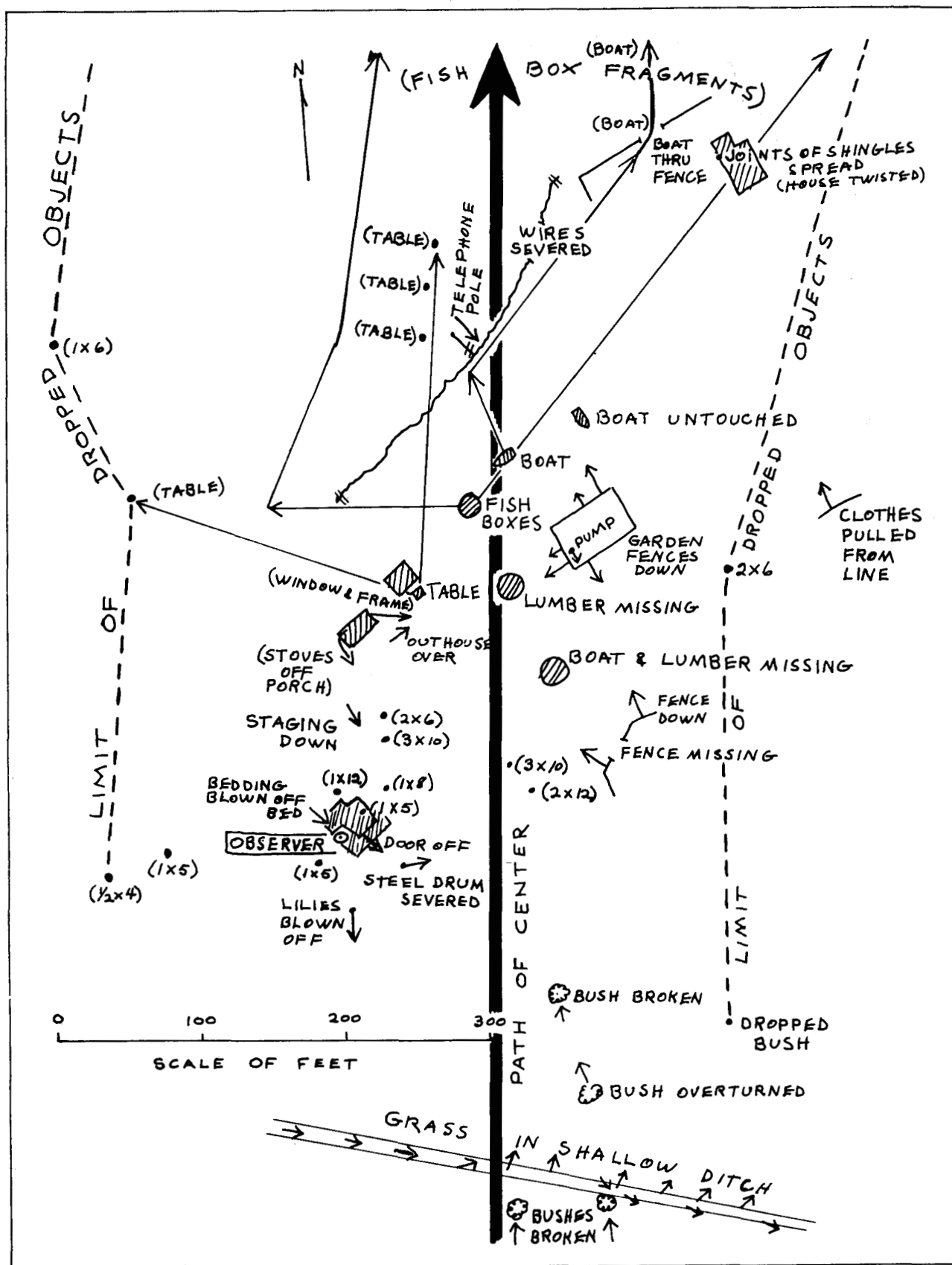


FIGURE 14.—Map of tornado's effects in observer's vicinity. Names in parentheses indicate dropped objects. Figures in parentheses show cross section dimensions in inches of dropped boards and timbers. Short arrows show direction of action. Long arrows show distribution of dropped fragments from identifiable sources.

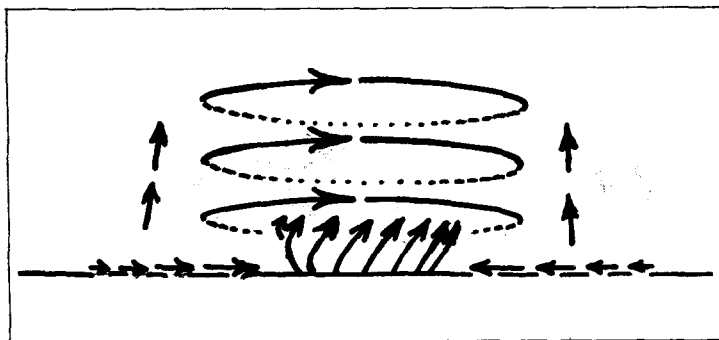


FIGURE 15.—Motions in the spray and sand bush as seen from the surface.

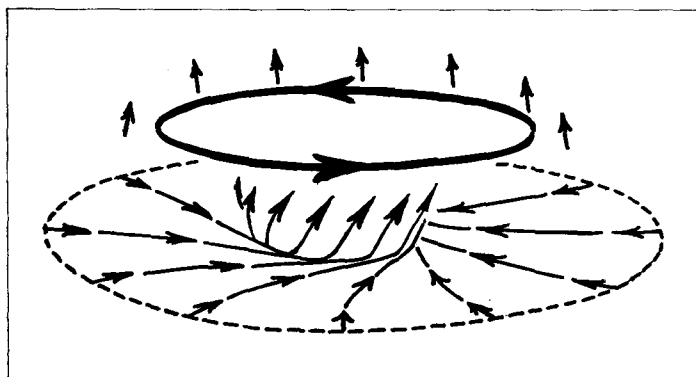


FIGURE 16.—Motions in the spray and sand bush as they would appear from an elevated station.

minutes backed to ENE force 7; then the squall ended abruptly. About this time brief damaging ENE winds were felt $\frac{3}{4}$ mile SE by S of my position. This might mean another tornado. One person saw three spray bushes over the ocean, two more than I saw, so there were probably five or six disturbances in all.

At 1700 EST the cumulonimbus was rapidly dissolving, with S wind force 2, variable to W force 2, then steady SSW force 3, increasing to force 4 at 1900. Temperature and dewpoint readings taken right after the storm were lost, but the pressure then (1700) was 30.07, or plus 0.07 over that of two hours before. At 1830 temperature was 83° F., which shows little if any cooling effect after the storm, and dewpoint was 79°, slightly above the pre-storm 78°. By this time thick altocumulus covered all but the far ESE sky, and convective clouds had disappeared.

Figure 14, as mentioned earlier, shows some representative effects of the storm's action. Winds were stronger and extended farther on the right of the track, but dropped objects were found farther to the left of the track,

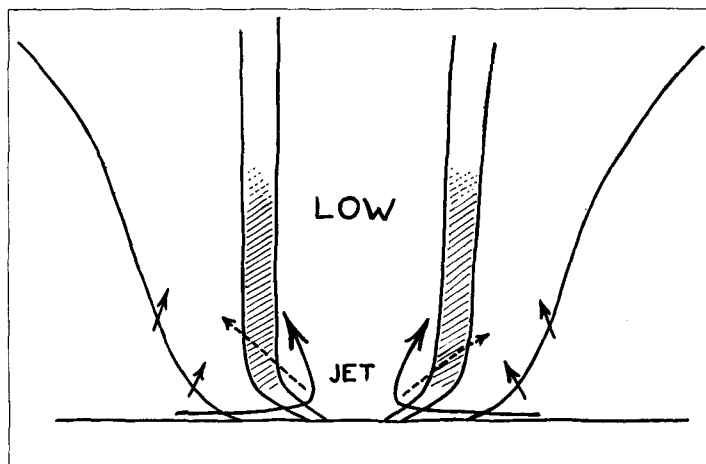


FIGURE 17.—Vertical cross section of vortex near the surface. Solid lines are schematic isobars. Shading is the "core wall" where gradient winds preclude convergence. The long arrows show the strong surface convergence under the wall, which changes to the jet upthrust inside the wall. Dashed lines show the jet cone of solid objects and particles lifted by the jet and evicted through the wall by centrifugal force. Short arrows show relatively weak updraft outside the wall.

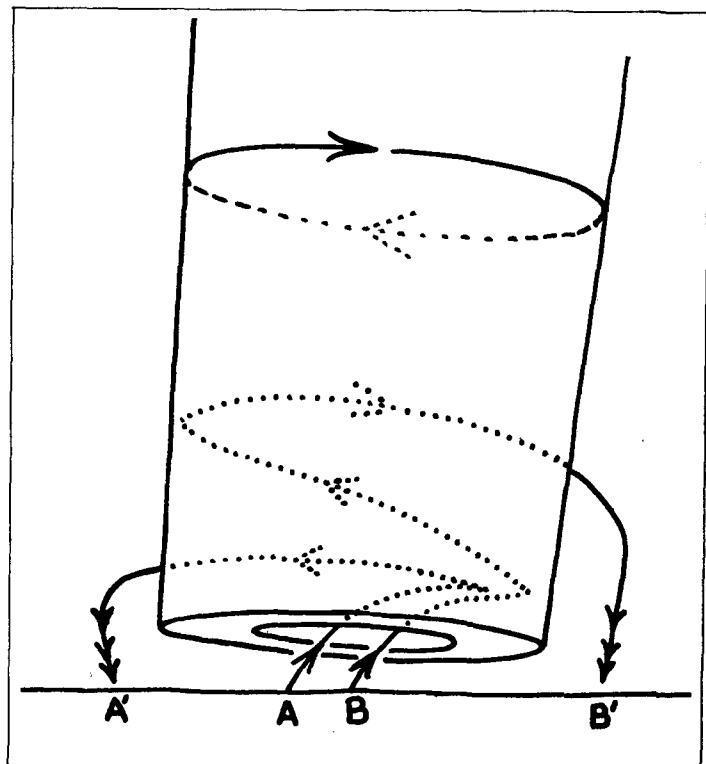


FIGURE 18.—Typical paths of objects hurled aloft by the jet; A—A' evicted through the core wall and eased to earth in the outer updraft, B—B' held captive for longer periods above center of jet.

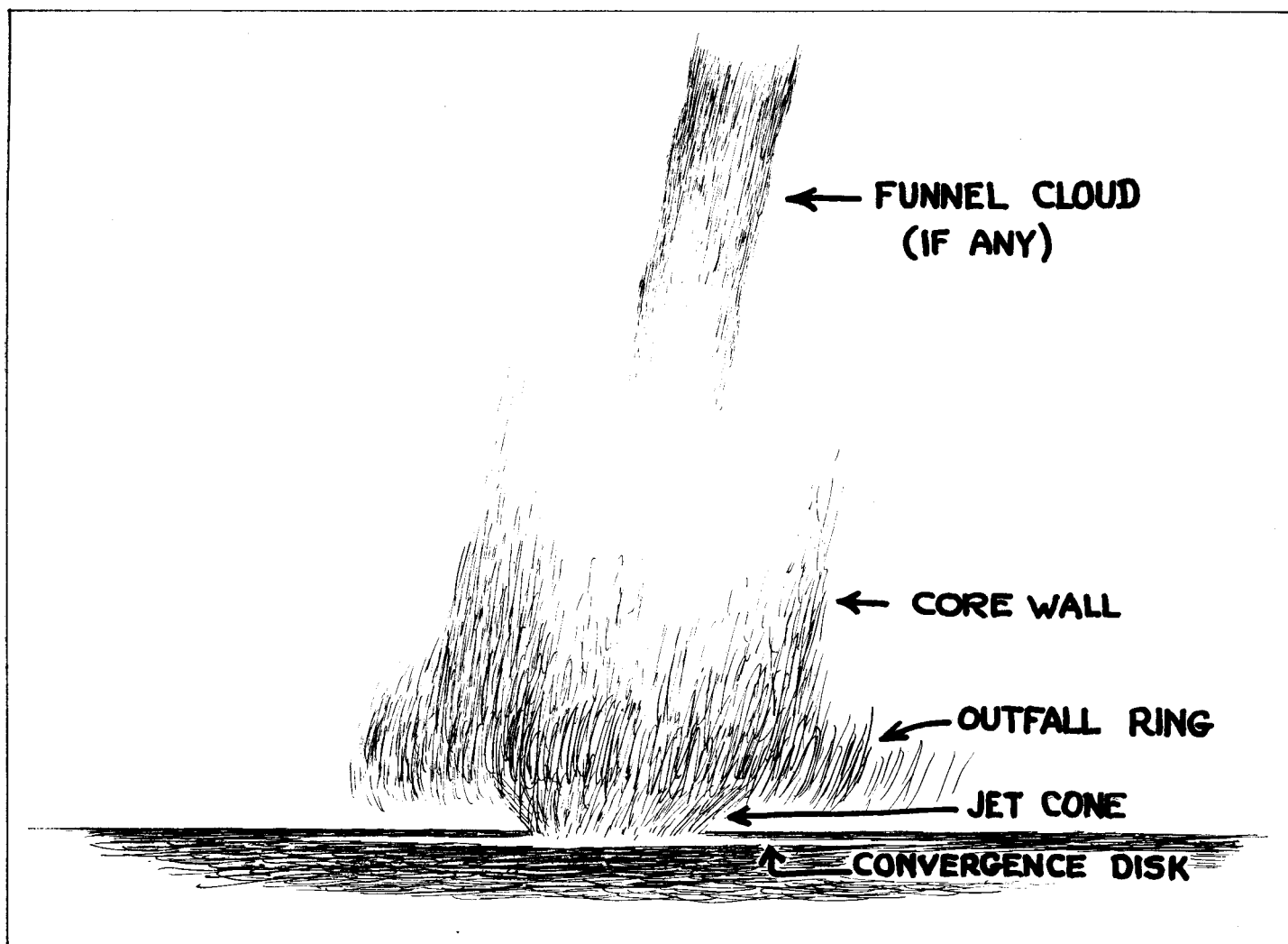


FIGURE 19.—Typical appearance of spray bush, with parts named in accordance with the author's jet hypothesis.

the overall width of their path being 600 feet. Wind effects comparable to those caused by hurricane force were seen over a path 320 feet wide. A few low pressure effects were seen, such as the door pulled from the observer's house, and a window frame and sashes pulled from the house next door toward the storm center.

4. MOTIONS IN THE TORNADO

The motions of sand and other objects observed in the sand bush as the tornado approached the observer are shown schematically in figures 15 and 16, and are interpreted in terms of air flow in figure 17. Some hints as to the movement of sand are shown in figures 11, 12a, and

12b, which are photographs of the sand bush. Horizontal circular movement 15 or more feet above the ground in what I shall call the core wall was the fastest of all observed movements in this tornado. One may hypothesize that the wind in the core wall rotates at gradient velocity and precludes convergence, except in the layer next to the ground. Here frictional drag destroys the gradient equilibrium and lets surface air rush under the wall in a converging disk and then turn suddenly upward into the low pressure at the core center. This results in a high-speed jet which apparently loses force quickly with height.

This jet is believed responsible for the prodigious feats of lifting and shattering observed in this storm, a tornado

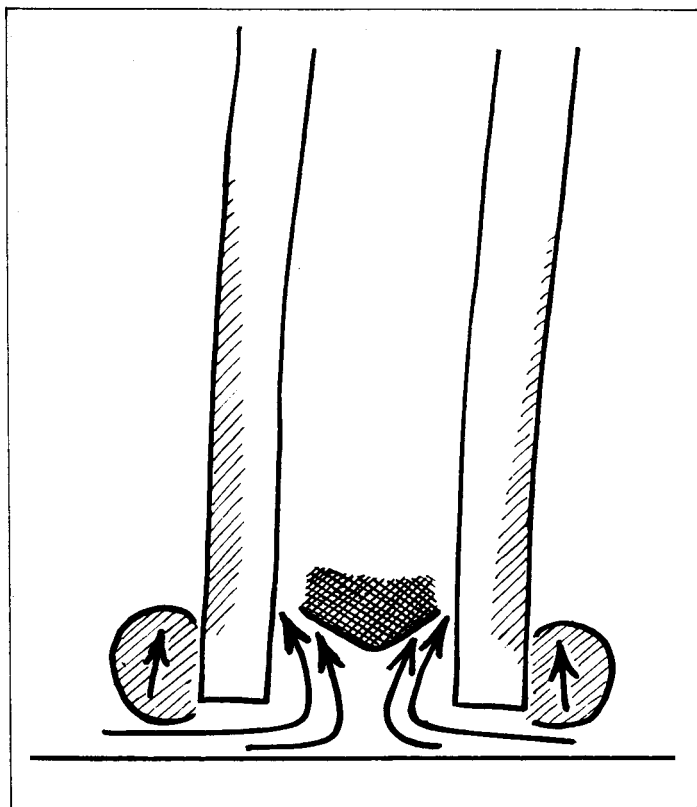


FIGURE 20.—This figure shows schematically the regions where lifted objects and particles were suspended in this tornado. Sand and spray tended to occupy the outer zones such as core wall and outfall ring (slanted shading), while heavier objects were seen suspended in the heart of the jet (the cross-hatched region). Departure of objects from these regions seemed to be slow and gradual, or even imperceptible.

of moderate intensity. Some objects lifted by the jet tended to fan out through the core walls by centrifugal force within a cone-shaped region, and when they reached the relatively mild updraft outside the wall, they formed a suspended ring and settled slowly back to earth. This sequence of movements is illustrated in figure 18. This process could also be seen in the spray bushes of the off-shore waterspouts—the flat spindrift convergence disk, the spouting jet cone in the middle, the vicious whirl of the core wall above, and the gentler motion of the outfall ring. This is shown in figure 19. Figure 17 presents in vertical cross-section the schematic isobaric pattern believed to be associated with the jet phenomenon.

The core wall, about 400 feet in diameter while near the observer, made one turn in about 5 seconds, which is rotation at 175 m.p.h. Velocity in the convergence disk near the jet probably exceeded 100 m.p.h. On Engagement Hill, low-flying sand showed that the disk extended

500 feet east of the center. The effect of the convergence disk, as indicated by the flying sand, was photographed and appears on the right-hand side of figures 12 a and b as a lighter area beneath the outfall ring.

Figure 20 shows schematically the regions where lifted objects and particles were suspended in this tornado. The sand and spray tended to occupy the outer zones such as core wall and outfall ring (slanted shading), while heavier objects were seen suspended in the heart of the jet (the cross hatched region).

5. SUMMARY OF FINDINGS

1. Waterspouts of the type described here are tornadoes.
2. The formation of these tornadoes was anticipated on the basis of oppositely moving, warm, humid air streams, provided both streams could partake of convective uplift in the same cumulonimbus cell. Warmth, humidity, and lapse rate favorable to vigorous convection in both streams seemed essential to tornadogenesis in this case. Likeness in these characteristics was more important than contrast.
3. Cyclonic circulations across the cloud base with vertical axis preceded, and gave strength to, tornado circulation of much smaller diameter which emerged from the cloud on a slant. Opposite edges of the cloud base, moving in opposite directions in tornado cyclones, probably give rise to frequent eyewitness reports of "two clouds coming together."
4. There was no evidence of downrush or outflow at the surface, and only isolated evidence of downrush aloft. The evidence favored the opposite—convergence and uprush at the surface.
5. Strong convergence at the surface was converted suddenly to a vertical jet near the core center. The converging air acquired rotary motion as it passed under the core wall.
6. The jet lifting effect was tremendous near the surface, but relatively weak a short distance aloft. Other tornadoes have, of course, lifted objects high into the clouds.
7. The lower portions of tornadoes 2 and 3 did not, while slanting, trail behind the funnel clouds aloft, but preceded them without help from the surface wind.
8. The funnel clouds lowered, rose, broke, and joined capriciously and with no apparent relation to the surface violence of the storm which in this instance raged steadily on until the final decline.
9. The funnel cloud need not come anywhere near the ground for the tornado to develop destructive power at the surface.

ACKNOWLEDGMENT

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REFERENCE

1. F. B. Dinwiddie, "Waterspouts over Croatan Sound, N.C.," *Bulletin of the American Meteorological Society*, vol. 27, No. 4, April 1946, pp. 172-173.

New Weather Bureau Publications

Technical Paper No. 29, "Rainfall Intensity-Frequency Regime: Part 4—Northeastern United States," Washington, D.C., 1959, 35 pp; for sale by Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C., price \$1.25.

Paper analyzes rainfall intensity-duration-frequency regime, with other storm characteristics, for duration of 20 minutes to 24 hours, areas from point to 400 square miles, and frequencies for return periods from 1 to 100 years, for the region east of longitude 80° W. and north of latitude 41° N.